Final Report

FUTURE DIRECTIONS FOR STRUCTURAL MECHANICS-FUNDAMENTAL RESEARCH ISSUES

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Dr. Terrence A. Weisshaar
Professor, School of Aeronautics and Astronautics
Purdue University
West Lafayette, Indiana 47907

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14. ABSTRACT

This effort had two goals: 1) to identify emerging research and development areas in the areas of flight structures and materials systems important to the future of the U.S. Air Force; and, 2) to define “Grand Challenges” that, if pursued, will provide future basic research programs that support Flight Structures development for the next half-century. Several distinct areas of research have been identified; we developed an identification process that we recommend be used for the future efforts. These research areas and the procedure are described within the report.

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1.0 Introduction and Summary of Work

This report summarizes a research effort entitled "FUTURE DIRECTIONS FOR STRUCTURAL MECHANICS-FUNDAMENTAL RESEARCH ISSUES" (Grant Number: FA9550-07-1-0037); this effort had two goals: 1) to identify emerging research and development areas in the areas of flight structures and materials systems important to the future of the U.S. Air Force; and, 2) to define "Grand Challenges" that, if pursued, will provide future basic research programs that support Flight Structures development for the next half-century. Several distinct areas of research have been identified; we developed an identification process that we recommend be used for the future efforts.

To achieve our goals, we conducted interviews, searched literature, conducted one workshop and organized a panel discussion at a National research conference. The workshop was held in Arlington, Virginia in October 2007; the panel discussion was held at the 49th Structures, Structural Dynamics and Materials Conference (SDM) in Schaumburg, Illinois in April 2008. A list of the October 2007 workshop attendees is included in the Appendix to this report. PowerPoint slides from presentations at the AIAA meeting are also included in the Appendix to this report.

In addition to research identification we achieved several other milestones. First of all, experts in the Flight Structures community came together on two occasions. As the result of discussions during these two meetings, the community was energized and encouraged to think about the long term future. Secondly, this effort gave the PI time to investigate alternative approaches to continuing the discovery effort involved in identifying future research of value to the Air Force. Flight Structures development depends strongly on advancements in scientific fields such as structural mechanics and materials. In addition, Flight Structures development depends on improvements in technologies such as manufacturing and processing.[1,2,3,4] Only be encouraging both top down and bottom up efforts on a regularly scheduled basis can we achieve our goals.

As mentioned previously, three approaches were used to identify and define research areas with high payoff. The first was surveying the industry. This was done by reviewing the literature and making one visit to Lockheed Aircraft, Ft. Worth. The second approach was to hold a workshop with experts as participants to attempt to identify, in a group setting, future topics of interest. The third approach was to use a Grand Challenge approach. This approach was begun at the AIAA Structures, Structural

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[1] "Maintaining U.S. Leadership in Aeronautics: Breakthrough Technologies to Meet Future Air and Space Transportation Needs and Goals," National Research Council, National Academy Press, Washington, D.C., 1998.

[2] "Aeronautical Technologies for the Twenty-First Century," National Research Council, National Academy Press, Washington, D.C., 1992.

[3] "Uninhabited Air Vehicles; Enabling Science for Military Systems," National Research Council, National Academy Press, Washington, D.C., 2000

[4] "New World Vistas-Air and Space Power for the 21st Century" U.S. Air Force, December 1995. The three volumes of the NWV Report contain information on topics from munitions to information warfare, including structures and materials. This report, although over 10 years old is still very timely.

Dynamics and Materials Conference in April 2008. All of these approaches have merit, but the most promising seems to be the Grand Challenge approach. We will discuss the results of each of these approaches and suggest a methodology that can be used in future research efforts.

1.1 Research topics developed from interviews and a workshop

The October 2007 workshop used a group of experts to identify potential research areas. There are advantages and disadvantages to expert workshops. The largest disadvantage is that participants knowingly or unknowingly advocate those topics with which they have greatest familiarity and those for which they have the greatest passion. The advantage of the workshop format is that experts have a vision of where the industry is headed and all have special knowledge of major roadblocks that need to be addressed. The October 2007 workshop participants were divided into two groups, aircraft and space systems; they identified a potpourri of analytical and experimental efforts that will foster flight structures system and component innovation as well as support rapid, new product development.

Specifics of the areas identified will be covered in Sections 3 and 4, however, the interest of most participants was integrating diverse technologies in a coordinated effort to produce new products or sustain existing products. Summarized, the recommended efforts are summarized as follows (these are not listed in prioritized order; the "raw" list of topics is included in the Appendix):

1. Multi-disciplinary optimization efforts (MDO), particularly topology optimization, to promote rapid identification and development of superior combinations of geometry and technologies, including materials, power systems and advanced actuators for both static and dynamic configurations. In particular we should support the development of advanced robotic flight structures – what today are known as "morphing aircraft" or "bio-inspired" aircraft such as the "flapping" aircraft or Micro-air vehicles now being proposed by AFRL. MDO efforts also support weight reduction efforts for existing evolving systems such as the F-35. This advanced capability does not exist today or if it exists is in an embryonic state..
2. Identification and support for new materials *systems* development of a new class of very advanced multi-functional materials, sometimes referred to as "symbiotic materials." These materials can change properties or "states" on demand by application of energetic stimuli, such as electric or magnetic fields, photonic energy to change mechanical, electrical or thermal states to produce system features such as "invisibility" or selective strength on demand enabling a mission adaptive component or system. This is discussed in Section 4.
3. Creation of new analytical algorithms to support rapid development of bio-inspired concepts, shape-changing vehicles and robotic aerodynamic components. This includes unsteady aerodynamic and aeroelastic theories to predict loads on rapidly changing air vehicle geometries such as wings whose planform areas and outer mold-lines change selectively and rapidly.

4. Development of new analytical algorithms to foster rapid integration of new and existing technologies. These new algorithms will provide new modeling methodology with the ability to exchange information across technology interfaces rapidly and would replace today's cumbersome "jury-rigged" techniques that simply lump together computer codes from one discipline with computer codes from another to create analysis systems with long run times and questionable accuracy. This also is related to MDO efforts.
5. Creation of a small, interdisciplinary "DARPA-like" research development group within traditional 6.1 research agencies to fund, at the seedling level, the exploration of emerging, fundamental research ideas that are relatively unformed or untested, have high risk, but have high pay-off. "DARPA-like" means that the members of the group executing this program would: 1) limited have tenure, typically 4 years; 2) be expert in their fields; 3) be drawn from academia, government and industry: and, 4) empowered to explore and perform with minimal direction and formal oversight. Within military organizations there is usually a "technology gatekeeper" who links the user organization to the scientific and technical world. Nothing transfers enthusiasm so much as working with or watching people who have faith, conviction and excitement about an idea. This involves champions of ideas who span organizational boundaries to fuel that excitement. There must be a high level person to provide support and adequate resources.
6. A broadly based effort that includes all analytical methods to enable or promote rapid insertion of new technology into new systems. These new analytical methods must be highly-efficient, validated, physics-based methods suitable for use at different levels of a multi-disciplinary simulation environment to foster the ability for virtual design, development, testing and deployment. The October Workshop participants called this goal "atoms to operation." This included (in addition to items 1,3,4 above) the following
    - New mathematical approaches to capture disciplinary interactions. The need for fundamental, reduced-order models that were easy to generate and high in information content was particularly stressed.
    - Integrated, multi-scale, multi-functional, system level simulation for flight vehicles
    - Optimized manufacturing tied into the system features as early as possible
    - Stochastic reliability
    - Test and analysis integration to reduce cost and yet speed development
    - Re-design of mathematical tools to meet challenges and new opportunities provided by faster, distributed, computing systems

Not surprisingly, this list is heavily weighted towards new product development. A list of Workshop participants and a raw summary of the aircraft portion of this meeting are included in the Appendix.

1.2 A New Methodology - The Grand Challenge Approach

Workshop participants nearly always advocate bottom-up efforts in which good research is expected to produce excellent future systems; these future systems are seldom defined by the participants. In fact, very often the participants cannot provide historical examples of fundamental research producing breakthroughs. As a result, we used not only a bottom-up approach, but also included an alternate approach. This approach is a top down approach in which Grand Challenges are defined beginning at the systems level; these Grand Challenges, if solved, will clearly lead to new military capabilities. With this approach, the sub-challenges and sub-sub-challenges required to address the Grand Challenges must also be defined as indicated in Figure 1-1. Some of these sub-challenges involve flight structures and some do not.

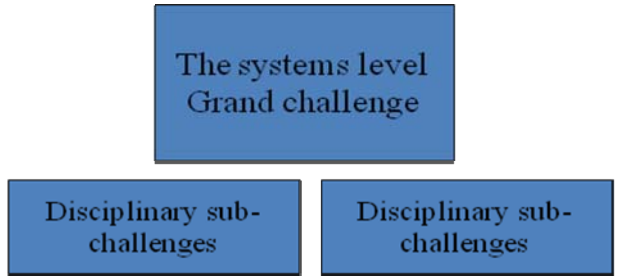

Figure 1-1– Components of a Grand Challenge involve combining constituent technologies or science

Several rules must be followed. The Grand Challenge must be stated first at a systems level; its solution must involve advanced software and hardware, and require challenging design trades and testing. For instance, we want to cast a problem as "provide eternal, unseen surveillance system to operate in a protected area" not "develop a long endurance airplane." One is a challenge; the other is a solution to the challenge and belongs at the sub-challenge level.

Tackling a Grand Challenge must be "DARPA-hard," not just a matter of manpower or money; solving the challenge should involve several possibilities, all of which involve substantial departure from those advocated today. The system defined by the Grand Challenge solution must be prototypical, but not necessarily optimal. Completing the Challenge must involve new thinking, in particular combining new technologies, some of which have low TRL, in a creative way not done before.

Figure 1-2 – ***Aurora Flight Science concept. Three UAVs dock, fold into a Z-wing to catch the most Sun by day, then stretch flat at night to conserve energy.***

An example of the results of this approach is the DARPA Vulture program that addresses "long duration flight" with a system, not a single aircraft. Long duration flight is a sub-task and can be solved by using a space system or an air system. Figure 1-2 shows one of the solutions to this problem. This aircraft uses a high aspect ratio wing design that can connect and disconnect parts for refurbishment and which can morph into a design to more effectively capture the

Sun's energy during daylight, but then morph back into the high aspect ratio design shown in Figure 1-3. The sub-challenges in this area include flight control, aerodynamic control, both steady and unsteady, and flight structures to allow attachment, re-attachment, section rotation and health monitoring.

Figure 1-3-Aurora Flight Science concept, shown in unfolded configuration

The following list of Grand Challenges, generated at the October Workshop, illustrates the type of efforts we are talking about. Some of these topics need clarification and refinement, but they are presented here as examples of the high level definitions that should be considered.

- Dispersed Air Mobility
- Personal Aircraft
- Disposable Aircraft
- Eternal Air-based Surveillance (this has since appeared as the DARPA Vulture Program)
- Massive Cargo Transport
- MAVs
- Ultra-efficient Hypersonic flight over long distances
- Reconstitutable, reconfigurable Space Systems
- Adaptive, morphing aircraft
- Robust air vehicles with 50 yr life span
- Deployable concepts/air assets
    - Systems emplaced, waiting for action
    - Systems in LEO/ Eternal flight
    - Deploy & Forget until needed

Some items on this list, for instance MAVs, are solutions to perceived problems while others, such as "ultra-efficient hypersonic flight over long distances,' is a capability and a current subject of strong interest to the U.S. Air Force. The adjective "ultra-efficient" is used to distinguish this challenge from current and past efforts.

Notice that in Figure 1-4, the sub-categories are listed as general functions or requirements that must be performed to ensure the success of the top-level solution. What are not listed are specific solutions. For instance, under the heading "propulsion" we have not listed "scram-jet" or any other solution. However, at some level we will need to bring in the operational environment that restricts solutions and requires innovation as well as defining with metrics what we mean by terms such as "ultra-efficient" or "long range." That is where the research needs and goals are identified.

Space systems, even more than aircraft, require advanced materials, mechanized, storable

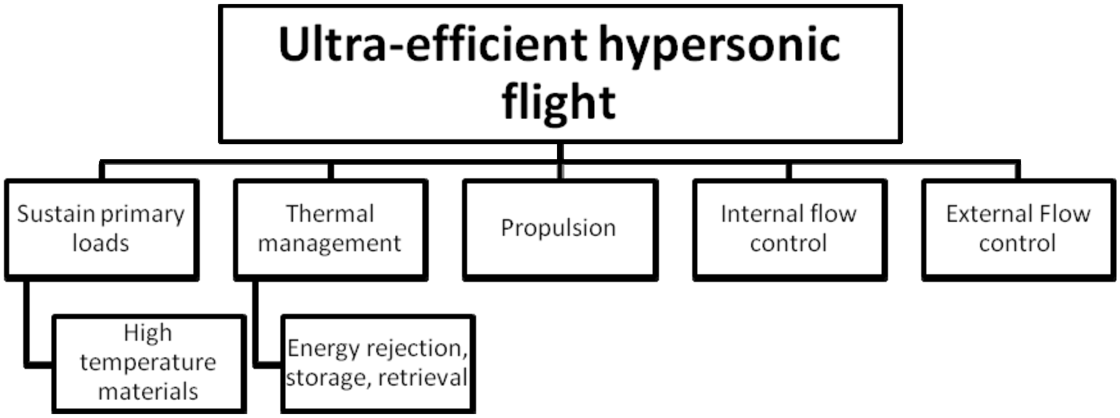

Figure 1-4 – The Grand Challenge of ultra-efficient hypersonic flight

structures and tremendous creativity for packaging and deployment. To illustrate a Space System Grand Challenge, consider Figure 1-5. This figure shows the design hierarchy of a system that uses a large space aperture. As the system definition flows to the right, more details and technical requirements emerge. Eventually, some of these details will involve technologies or theories that are immature or do not exist. In addition, when we read the requirements from left to right we might be tempted to take existing technology and construct the system. If we already have a solution then we do not have a Grand Challenge.

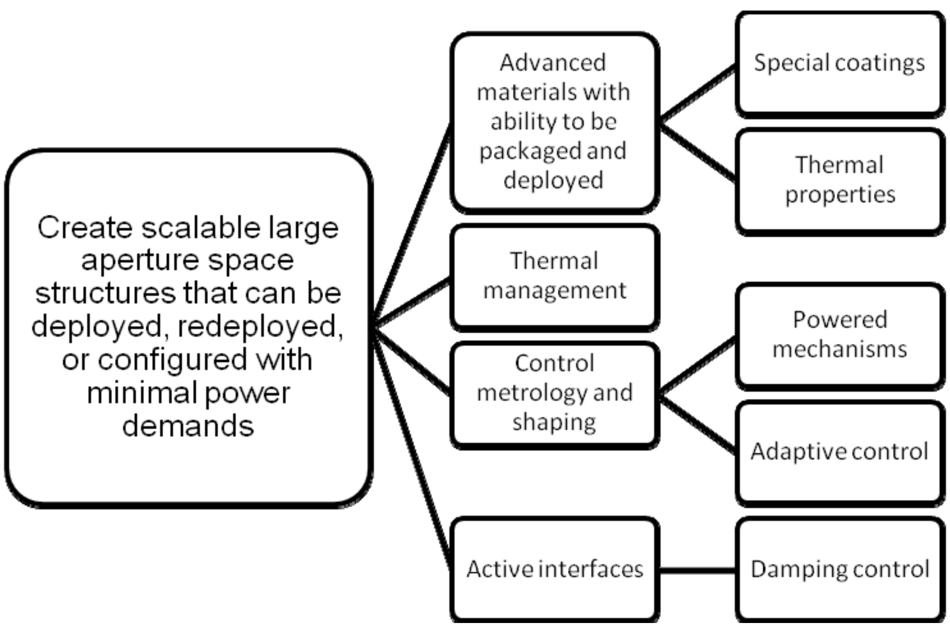

Figure 1-5 – The Grand Challenge of ultra-large aperture space systems

On the other hand, if some of these required blocks display only one or two choices we might wonder if the choices should be expanded. If, for instance, we have powered mechanisms, but they are inefficient or heavy then we might examine the requirements for different actuators or different approaches altogether.

In summary, the Grand Challenge approach to research identification is a top-down systems engineering approach, beginning by identifying general "fuzzy" needs and capabilities likely to appear or be required in the future. This leads to and requires top-level discussions that are "warm-up exercises" that must precede technical discussions and anchor technology advances to measurable system goals. The next few sections focus on how and why the future of military technology is likely to develop and importantly, why the exact details of the future is so hard to predict.

An expanded discussion of research needs for Space Systems is covered in Section 3 while Aircraft research is discussed in Section 4. First, let's look at general features of military developments and doctrine and to identify technical developments in flight structures and materials likely to be important drivers or enablers in the development of new vehicles or components.

2.0 Background – How do we Identify forces driving technology for the next half-Century?

Research prediction and prioritization is depends on the evaluator's background, as well as *zeitgeist* ("spirit of the times") that elevates some technologies and suppresses others depending upon current needs. For instance, the Cold War produced far different perceptions of the future than does the war on terror.

History teaches very strong lessons. While progress at the systems level and the component level is unpredictable, one sound strategy for funding science and engineering is to allow spending for untried, "unneeded," unpredictable research that can conceivably have an effect on future military doctrine. This is one reason to advocate DARPA-like organizations.

However, this begs the question, where is the unneeded, untried research likely to lead at the systems level?

The difficult choices faced by funding agencies are summarized in Figure 2-1, adapted from a presentation originally presented by Dr. Mark Millis of NASA Glenn

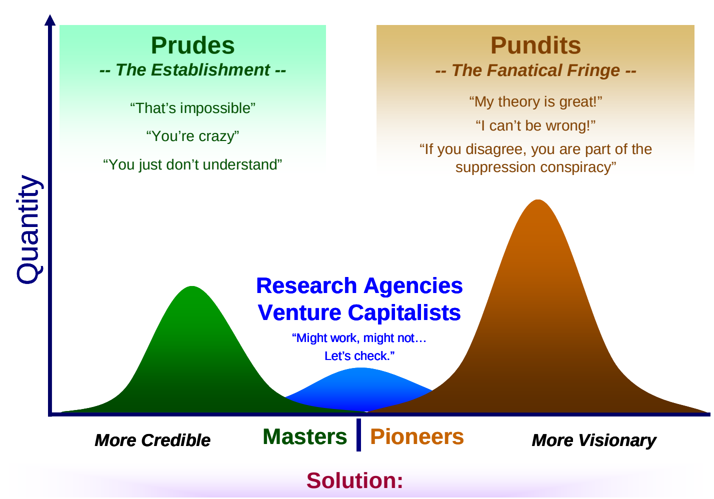

Figure 2-1- The choice between high risk and low risk research requires risk taking

Research Center. The function of funding agencies is to draw researchers together with funding agencies to debate the merits of research and then advance science and technology.

Research funding choices tend to focus on near term problems. A 1999 Defense Science Board study concluded that *"The DoD system of technology development and system acquisition is a relic of the past and is not well suited to cope with the critical national defense problems of the future. …(the) current DoD and Service science and technology laboratory system tends to concentrate on technology related to military systems that are already developed."*[5] If current research funding is tied to current systems, then the revolutionary future never has a chance to develop at that funding agency. Everyone knows this, but few act on that knowledge.

Two features drive science and technology development: 1) industry values technologies that reduce the time to develop and market its current products; 2) new product innovation requires the ability to combine or exploit technologies in new ways. "Technology" includes new analytical techniques and new production processes inserted into the "conceive-design-build-test-operate" (CDBTO) chain to reduce manpower required or to improve product quality.

New product development depends on a combination of known and "unknowable" factors. Technology breakthroughs often depend on "curiosity driven research" conducted by individuals in university, government or industrial facilities. One feature of curiosity driven research is that it is funded at very low levels and has few champions in funding agencies. Technology development and technology mixing/integration often rely on serendipity.

Central to the challenge to create revolutionary changes is the realization that future flight structures research cannot be a "stove-piped" effort. The list of topics provided in Section 1.1 reflects this cross-disciplinary requirement. Cross-discipline collaboration has at least four needs.

- The need for cross-discipline optimization, design *and* education to increase chances of breakthroughs such as innovative capabilities – the Aurora Sciences long endurance system shown in Figures 1-2 and 1-3 is an example.
- A systems level understanding of how all disciplines contribute and interact and the development of "translation" methods to convey information across disciplinary interfaces
- The need to perform and enable parallel, as opposed to serial, design efforts with timely information flow
- Promoting social and organizational changes to promote "multi-cultural" efforts. Multi-cultural means not only combining different disciplines, but combining different roles, such as analyst, designer, test personnel and management (including contracting personnel) to promote cross-disciplinary thinking and "opportunity awareness."

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[5] 21st Century Defense Technology Strategies, Defense Science Board 1999 Summer Study Task Force, Volume 1.

2.1 *What events and allied developments are likely to affect flight structures technologies and create large changes in how we analyze, design, construct, test and maintain flight structures for a myriad of existing and future designs?*

We have stated again and again that Flight Structures is not a single discipline, it is a combination of technologies that contribute to system concepts, advanced materials and manufacturing processes; "Flight Structures" is a complex system that is part of an even more complex vehicle and organizational system. "*What events and allied developments are likely to affect flight structures technologies and create large changes in how we analyze, design, construct, test and maintain flight structures for a myriad of existing and future designs?*"

Answering this question is difficult; technological progress is influenced by complex social and technical processes. In the military prediction arena, Colonel C. G. Warner points out that successful air campaign concepts depend on four inextricably linked factors: *doctrine, operational concepts, organizational structures and finally, technology*.[6]

Doctrine plays an important role in advancing or retarding emerging, embryonic technologies. Different combinations of technologies and doctrine produce very different results. A prime example is the employment of new tank designs with German blitzkrieg tank warfare early in World War II and the contrast with the French who simply added the new tank technology to existing organizations and were outfought.[7] In fact, doctrine always lags technology, even when new advanced weapons are placed in the field.[8]

A doctrine that emphasizes air/land battles, as the U.S. Air Force did in World War II, or nuclear deterrence, as we did until the demise of the Soviet Union, leads to different organizational concepts and very different technology priorities. The emphasis on a certain doctrine can exclude technologies such as unmanned aircraft or cruise missiles in favor of ballistic missiles, as it did during the Cold War.

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[6] Col. Christopher G. Warner, "Implementing Joint Vision 2010: A Revolution in Military Affairs for Strategic Air Campaigns," Air University Press, Maxwell AFB, Alabama, April 1999, pp. 3-4.

[7] The German doctrine of blitzkrieg emphasized individual initiative, opportunism and exploitation. The French emphasized a carefully orchestrated attack, with tightly controlled "harmony." Perhaps there is lesson to be learned for the military laboratories about the dangers of tightly controlled "roadmaps."

[8] "The unresting progress of mankind causes continual change in weapons; and with that must come a continual change in fighting…changes in tactics have not only taken place after changes in weapons, which is necessarily the case, but … the interval between such changes has been unduly long. This doubtless arises from the fact that an improvement in weapons is the work of one or two men, while changes in tactics have to overcome the inertia of a conservative class; but it is a great evil It can be remedied only by a candid recognition of each change by careful study of the powers and limitations of the …new weapon, and by a consequent adaptation of the method of using it to the qualities it possesses, which will constitute its tactics. History shows it is vain to hope that military men generally will be at pains to do this, but that the one who does will go into battle with a treat advantage-a lesson in itself of no mean value." Adm. A. T. Mahan, ***The Influence of Sea Power on History, 1660-1783***, Little-Brown & Co., Boston, 1918, pp. 9-10 (cited in I.B. Holley, Jr., *Technology and Military Doctrine, Essays on A Challenging Relationship*, Air University Press, Maxwell, AFB, Alabama, August 2004.

Col. Warner points out that, whatever else we define as a capability for our forces, a successful Air Force is defined by *"ferocity, rapidity, destructiveness and disproportionality"* required to *"effect a 'state change' in (an enemy's) ability to adapt to an attack."* Using this objective, Warner identifies low observable platforms, LOP, as an essential part of a strategic air force. He goes on to list four tenets of the tactical philosophy of LOP: avoid detection; if detected, evade and escape; if engaged, survive; and, re-cloak to an unobserved status. Unfortunately, for our purposes of describing investments, discussion of LO technology is restricted by security concerns. It is however, a portion of certain general features we will discuss later.

To predict "future technologies" we must also remember that the development of new or improved system component technologies serves two different military system communities. The first community, ***the sustainment community***, is concerned with improving the performance of well-established products such as aircraft in the current inventory. In this case, technology strengthens current doctrine approaches. The second community served by technology is the ***disruptive system community***. This community often develops systems that change established doctrine, but for which there is no current military requirement.

The technologies that enable disruptive military systems result in products (such as airplanes or machine guns) that few predicted, but which make obsolete well-established products.[9] One feature of disruptive technologies - and the disruptive systems they enable - is that they begin with no established customer need or use for the foreseeable future. The Wright Brothers flight effort was curiosity driven; it was not driven by the need to replace commercial train or ship travel or military ordnance delivery. This feature of disruptive technologies obscures the "search for the future" since search results are biased strongly by current problems; future vision often appears bizarre or unwarranted.

Disruptive technologies develop products that are unknown today; often the effects of the products are unknowable. A good example of this difficulty is the development of the laser. At the time of its development four decades ago no one could predict how widespread lasers would become in our commercial economy, from laser surgery to supermarket checkout counters, or how important lasers would be to the military. Who in 1960 could answer the question "How will lasers influence supermarket operations?" with anything other than the simple answer – "they won't."

2.2 A pessimist's view of the future-the rise of new products without new Flight Structures research

One view of the future is that *"military systems will improve, but the only thing different is how we combine the technologies, not whether we make fundamental research advances."* This view requires us to believe that military doctrine and the challenges we face will remain stagnant and that technology is mature all across the board. For

[9] Clayton Christenson, ***The Innovator's Dilemma; When New Technologies Cause Great Firms to Fail***, Harvard Business School Press, Boston, Massachusetts, 1997.

instance, there is no doubt that, one-half century from now, unmanned air vehicles (UAVs) will be prevalent in military system operations. Networks of unmanned and manned aircraft and unmanned Space assets, such as that shown in the cartoon in Figure 2-2, will be blended together to form lethal systems that exchange information and execute tasks based upon the free flow of timely information and system awareness.

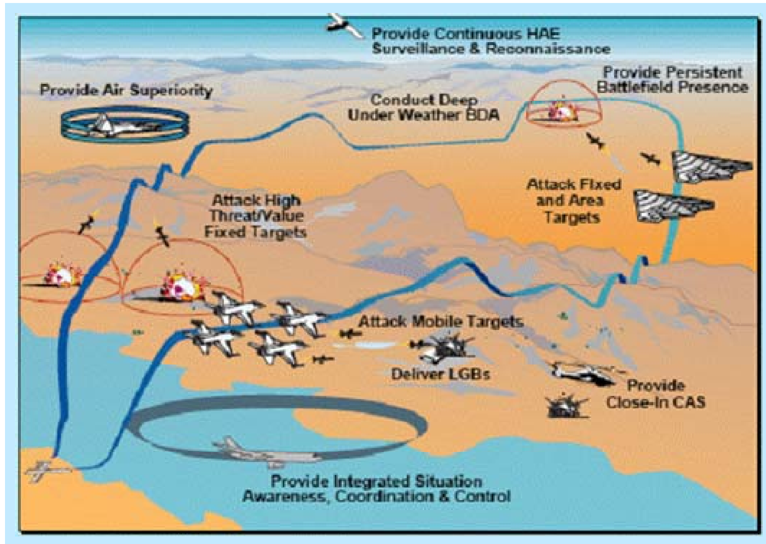

Figure 2-2-Net centric, robotic, integrated battlefield of the future

Chaput[10] compares mixed military manned/unmanned systems to a civilian taxi dispatch or pizza delivery service. The interesting aspect of these military system visions is that no individual technology developments are singled out as being required to achieve its revolutionary goals. The argument is: *"of course, we need larger computers and better algorithms for control of swarms of vehicles, but no radical technology change. We simply need to reorganize technologies or more wisely use those we already have."*

Will flight structures technology be any different in these future systems, and, for that matter, does it need to be different? This is the Flight Structures researcher's nightmare, *"revolutionary new system, and no new Flight Structures technology required."* The PI does not believe this to be true.

Flight structures research focuses on two important industrial product quality goals: *production of light-weight designs with structural integrity and reliability; and, production of designs with high quality*. No matter how revolutionary the products themselves, there are several over-arching requirements that industry sets for its products. These goals are:

- Improving product quality - High quality products require a wide variety of analytical methods and process improvements. Analytical methods range from those based on first principles to sophisticated structural finite element methods and computational fluid dynamics codes. These methods are usually used to resolve technical issues related to performance and efficiency.

[10] Armand Chaput, "Aerospace Technologies- Challenges and Opportunities for Future Combat Air Systems," AIAA, 2007.

- Integrating existing component technologies into a quality design – Analysis and testing are important to resolve issues related to synergies with other technologies or size the required components.
- Reducing product development time – Analysis and testing go hand in hand to reduce risk during development programs.

Figure 2-3, due to Dr. John McMasters of the Boeing Company, shows the difficulty of defining future research basic programs. It is the fundamental research in the bottom half of Figure 2-3 that is not targeted by formal roadmaps, but which has the ability to pay large dividends if successful.

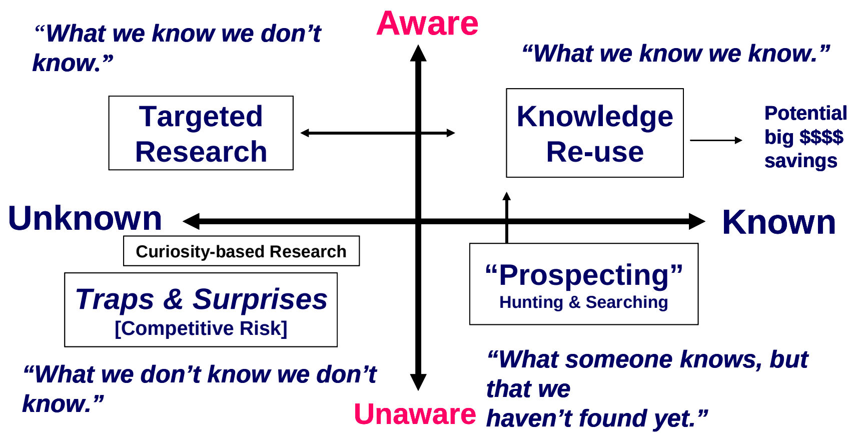

Figure 2-3 – Four different research approaches

2.3 Summary

Scientific discovery is unpredictable. There is a constant tension and struggle to advance new ideas in a world of orthodoxy. Technology development is driven both by scientific progress and progress in other technologies that makes realization of science, in the form of devices, possible.

Innovation in technology development and in the use of these developments is similarly hampered by orthodoxy and limited funding. Research funding prioritization is difficult in a volatile world in which everyone clamors for acceptance of "their idea." The fact that military doctrine drives most military research is another factor that hampers predictions for the future and also hampers prioritization of research funding. In many cases, "out-of-the-box" research is simply not affordable given other pressing day-to-day problems.

Some areas of research will always be with us. Speeding products to market is a continuing challenge. Fostering innovation is another. Out-of-the-box research requires a champion who often puts his or her career on the line. The fact that doctrine always lags technology does not change matters. One way to help advance out-of-the-box research is to envision out-of-the-box systems and the technologies that feed them. In the next two sections we will suggest some of these systems and also connect technology progress requirements to them. We will consider the Space Systems area in the next section.

3.0 Space Systems for the next half-century

During the past 50 years there have been enormous changes in how we gather information and distribute it. Fifty years ago we gathered information primarily by aerial reconnaissance. The downside to this was that U.S. spy airplanes were shot down at inappropriate moments. Satellite surveillance with advanced sensors and optics changed this forever.

Among the most important military systems in the United States are the assets deployed in space. These assets, now focused on intelligence gathering, navigation, weather monitoring and communications, are indispensable. To lose these assets in a time of military emergency would be disastrous.

The first military space systems were very mission-oriented – when a new space capability was identified, a dedicated spacecraft and support structure was created. This dedicated "point design" approach is appropriate during early technology development which emphasizes the creation of new capability. During the past half-century, Earth-orbiting spacecraft have evolved from simple, small spacecraft into high technology systems with complex, system-of-systems architectures. Today we are well beyond the "discovery" era and now design space systems where issues such as life cycle cost, system scalability and upgradeability are extremely important.

Future military space efforts are difficult to predict for several reasons, not the least of which is a U.S. national policy, sometimes referred to as "sanctuary," that keeps the "heavens free of weapons." In addition, most military space efforts are shrouded in tight secrecy. The presence of "Black Projects" both acknowledged and unacknowledged can only be assumed. The author possesses no special information in this area. However, there are two forces that are likely to change the direction of military space research.

First of all, the number of countries capable of launching satellites into space has increased dramatically during the last 10 years. The increased ability of smaller nations to contract out the design, building and launching of small, relatively cheap satellites poses a challenge for future commercial and military systems. These foreign satellites are usually relatively small but they have the capability of interfering or rendezvousing with U.S. satellites in Low Earth Orbit (LEO).

The second feature of U.S. military satellite development is that increased intelligence information is required to ensure security from an increasing number of world-wide threats. Satellites in LEO are easier to launch than those in Geosynchronous Orbit (GEO), but their orbits are predictable and their dwell time over a target is less. Finally, the unpredictability and uncertainty of world geopolitical events makes it difficult to address needs in a timely "responsive" fashion. The time to develop and launch satellites is very long (several years) and certainly not "responsive."

Military space system development and operation are extremely expensive. The cost of developing complex hardware, launching systems, and constant, detailed "care and feeding" requires enormous budgets and a great deal of lead time. In addition, most DoD

space systems are useful only for a single, well-defined mission, and cannot respond to sudden, unforeseen, unpredictable changes in the geo-political environment.

3.1 Four Space System developments likely to occur during the next 50 years

Four developments will change military space system design and deployment during the next half-century. The first is the obvious role of technology that sustains development of better, less costly, space systems even as they are saddled with more and more requirements. The second development is a migration of essential intelligence assets from Low Earth Orbit (LEO) to Geosynchronous Orbit or Geostationary Orbit (GEO). This will be the response to threats to these assets from small, relatively unsophisticated satellites and satellite weapons and the need for near continuous surveillance of some areas of the Earth.

The third development will be a fundamental change in space system design philosophy that will allow space systems to be upgradeable on-orbit and responsive to changes in technology as well as unforeseen threats. The fourth challenge will be the challenge of space warfare which will require protection of military and civilian communication assets and the ability to reconstitute space systems quickly in times of national emergency. As noted in Section 2, technology usually precedes doctrine.

3.2 Military Space Systems and Space Doctrine-Background

During the past 50 years two political events profoundly influenced the way Space is used today by the military and intelligence agencies. The first was President Eisenhower's belief that knowledge of the Soviet Union's military intent was vital to preventing war. The second was the use of space communications, global positioning capabilities and command and control in the 1991 Gulf War; this war was called "America's first Space War."

In February 1955 the *Technological Capabilities Panel* of the Scientific Advisory Committee of the Office of Defense Mobilization (TCP) headed by James R. Killian, Jr., issued a report "Meeting the Threat of Surprise Attack." This was later simply referred to as the "Killian Report."

The Killian Report helped to accelerate development of both the ICBM and observation satellites; one recommendation was the immediate initiation of a program aimed at launching an American scientific satellite. Nearly 50 years later we can look back at a clear successful execution of projects begun as the result of the Killian Report.

The Air Force Space Command (AFSC) has defined their future needs as part of a published, public technology development roadmap addressing the challenge of "responsive space." Technology development objectives are summed up in one sentence: "A globally integrated aerospace force providing continuous deterrence and prompt engagement for America and its allies…through control and exploitation of space and

information."[11] This goal requires "operationally responsive" operations of U.S. on-orbit space assets to support the full military spectrum of world-wide operations, as well as systems that have multi-mission or multi-role capability. The AFSC roadmap leaves much unsaid about what the term "full military spectrum" means.

Today there is a great deal of discussion about National Space policy and the closely related field of military use of space. A well-regarded report by Lupton[12] defines four "Space Doctrines" and details their attributes. Lupton's four doctrines and their attributes are summarized in Figure 3-1.

	Primary Value and Functions of Military Space Forces	Space System Characteristics and Employment Strategies	Conflict Missions of Space Forces	Appropriate Military Organization for Operations and Advocacy
Sanctuary	• Enhance Strategic Stability • Facilitate Arms Control	• Limited Numbers • Fragile Systems • Vulnerable Orbits • Optimized for NTMV mission	• Limited	NRO
Survivability	Above functions plus: • Force Enhancement	• Redundancy • Hardening • On-Orbit Spares • Crosslinks • Maneuver • Less Vulnerable Orbits • Stealth • Reconstitution Capability • Defense • Convoy	• Force Enhancement • Degrade Gracefully	Major Command or Unified Command
Control	• Control Space • Significant Force Enhancement		• Control Space • Significant Force Enhancement • Surveillance, Offensive, and Defensive Counterspace	Unified Command or Space Force
High Ground	Above functions plus: • Decisive Impact on Terrestrial Conflict • BMD		Above functions plus: • Decisive Space-to-Space and Space-to-Earth Force Application • BMD	Space Force

Figure 3-1– Lupton's Four Space Doctrines and their attributes

Figure 3-1 indicates that we have moved from the original "Survivability" doctrine espoused by President Eisenhower and dealt with by the Killian Report, to "Survivability" made possible and necessary by the 1991 Gulf War. When, not whether, we move to the "Control" or "High Ground" doctrines is anyone's guess, but the events that force this are already in motion. Technology development will quickly follow.

Response to future critical challenges in remote regions of space surrounding the Earth must happen within hours or minutes after a challenge is detected. To implement the Air Force goal and others like it, two components are required: (1) operationally responsive launch vehicles; and, (2) development of affordable, multi-functional, operationally responsive space systems.

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11 "Strategic Master Plan – FY06 and Beyond,: U.S. Air Force Space Command, 2004

12 David E. Lupton, "On Space Warfare: A Space Power Doctrine," Air University Press, Maxwell AFB, Alabama, June 1988.

The first component, responsive launch vehicles, is being addressed by public and private launcher initiatives. The second goal, responsive space systems, like future Space Doctrine, assumes that the exact nature of the threat is known with enough advance knowledge so that the “responsive” system can be built well ahead of the need and either stored in a depot on the ground or on-orbit.

To respond to future challenges, future space systems will be collaborative, and adaptive. These systems will have drastically reduced acquisition time, reasonable cost in comparison to their military value, and provide orbitally-flexible, platform-reconfigurable, mission-adaptive, collaborative capabilities in space to radically improve National defense.

Affordable, robust, operationally responsive space systems are not feasible without changes in the space system design process and without development of new technologies and technology ensembles that do not exist today or are immature at best. Accomplishing this goal will be a major focus of future research and development.

3.3 Special problems faced by all Space Systems

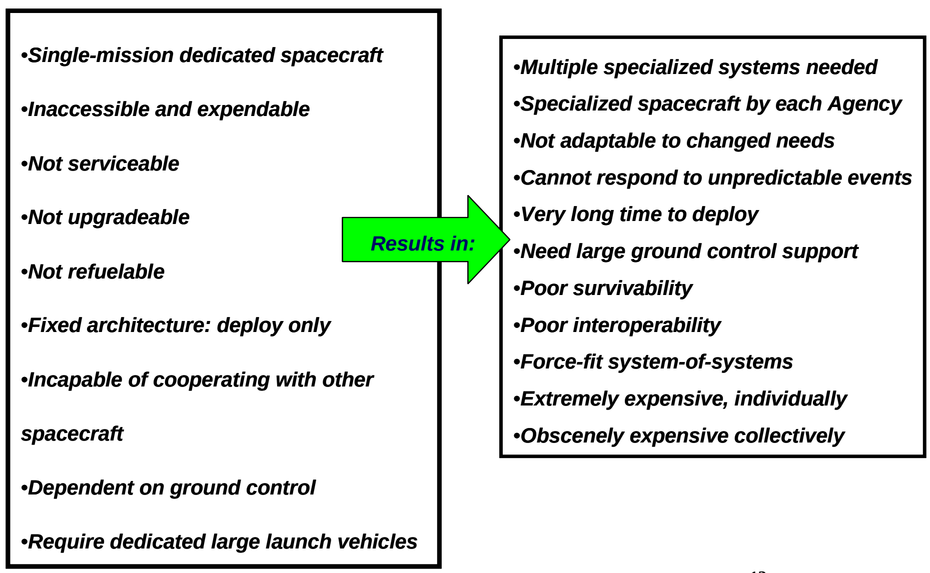

Figure 3-2– Today’s satellite system features (Bekey[13])

While the technologies used to develop and operate space systems have improved by orders of magnitude during the past few decades, the way we design, develop and deploy large satellite systems has changed very little. Space systems are obscenely expensive and take a great deal of time to manufacture, assemble and check out. The challenges of on-orbit upgrading and refurbishment have favored systems with limited lifetimes, with capability frozen well before launch, and with severe limits on changing operational features once the system is launched. As shown in Figure 3-2, this approach limits the scope, affordability and effectiveness of current and future systems.[13]

[13] Ivan Bekey, ***Advanced Space System Concepts and Technologies***, The Aerospace Press, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2003. This book is a “must have” for anyone considering the future of Space Systems.

To cope with these problems, new doctrines, new technologies and new types of space system will appear with three dominant features not present in today's systems. These are: 1) on-orbit responsiveness, 2) scalability and 3) adaptability. ***Responsiveness*** is the ability to quickly change operational features or configuration to adapt to changing requirements or changed environment or to quickly reconstitute capability after degradation or elimination of assets. ***Scalability*** is the ability to upgrade an asset as new hardware technologies are developed and the ability to gracefully degrade in the presence of failure of some components. ***Adaptability*** includes the ability to perform diverse mission operations in an uncertain, multi-faceted threat environment and to re-configure hardware and software or operations in the presence of a component failure.

3.4 Six Space System challenges and related research goals

During the AFOSR Workshop in Arlington, Virginia, an expert team debated space system challenges. During nearly two days of discussion, these experts agreed that there are at least six challenges to space system development and operation. These are: 1) thermal kinetics/management to control or eliminate waste heat; 2) spatial/temporal metrology to control sensor shape; 3) combating structural degradation by a hostile environment; 4) reducing time to qualification/certification/launch; 5) providing increased data bandwidth; 7) countering electromagnetic vulnerabilities. Let's consider in more detail the first four of these six challenges.

While space system thermal energy is abundant, so much so that a large system is needed to reject it power is always at a premium. We know that, in the RF/optics/power laser worlds, efficiency is only about 20%. Thermal management components comprise a significant percentage of the typical satellite system's weight.

Improved concepts involving integration and exploitation of the fundamental physics related to energy management, thermal conduction and thermal control could yield dramatic reductions in weight and energy efficiency. A technology goal on the order of 95% would be a challenging objective. Examining the physics involved in such a quest to determine of this is an executable goal is a necessary first step.

In addition to improving efficiencies of on-board space system devices that generate heat as a by-product we need to examine the technology used to design and build cooling systems. Since the organization and placement of energy consuming devices is significant, the development of thermal management technology that enables new design strategies is important. For instance, the ability to design a distributed, non-monolithic energy consuming system would help, since components can be turned on and off at the proper times, depending on need and thermal environment.

Finally, multi-functionality of the spacecraft structural bus components will improve efficiency. This leads to the ability to harvest, store, shift, deliver, and reject energy on demand. It enables a thermal energy network, part of a broader functional network, with thermal path planning to direct energy and allow conversion of wasted thermal energy to another energy form instead of rejecting it.

As mentioned previously, the rapidly growing number of nations with space assets will drive us to consider countermeasures to protect both military and commercial satellites. In the area of intelligence gathering, an effective countermeasure is to increase the altitude of the orbit above the Earth to get out of range of small satellites.

This means that intelligence gathering must migrate from Low Earth Orbit (LEO) to Medium Earth Orbit (MEO) or better yet, can move to Geo-stationary Orbits (GSO) very far from the Earth. An additional advantage of GSO's is that the satellite can dwell indefinitely over trouble spots. The problem with this strategy is that sensors, particularly optical sensors, must grow in size as satellite altitude increases.

As space surveillance systems migrate to higher orbits, larger antennas and mirrors are required. These elements must be light weight and are thus very flexible. ***Metrology*** involves knowing where the spacecraft or space system is in space and time. This means relative positions of all the components and positions with respect to a reference system such as the Earth. This is particularly important for large antennas or optical mirrors and the development of new systems. One challenge is to improve the way and the accuracy of how structures report, but not necessarily control, relative positions of critical elements to sub-nanometer levels and temporal resolution to sub nano-second levels. These measurements determine the ability to compensate for structural deflections and deformations which impact ability to deploy effective optical/RF systems.

Structural state awareness. Future systems will be upgradeable and reconstitutable. It is important that these systems monitor their performance and be able to adapt to component failures while still being able to function. This involves a new look at structural health monitoring that moves beyond simply telling the operator what is happening, e.g. how strong, how cold, how effective a system is.

This next step involves making life cycle predictions and identifying patches or repairs required in real-time. This would ensure mission effectiveness and ability to continue the function or mission. A stretch goal is to improve mission capability by an order of magnitude for the same system weight and volume.

This health monitoring capability is a key element that enables system re-configuration and responsiveness. Advanced systems will reduce design uncertainties at reduced safety margins and eliminate redundancies. Closely related to health monitoring goals is development of sensor technologies that enable wide-spread monitoring and perhaps multi-functionality. It is also possible that materials could be developed that sense structural damage and repair it.

Reducing certification times from today's approximately five years to less than three months is important to future responsive systems. A stretch goal would be, one decade from now to reduce certification time from five years to four years. Achieving this goal would enable rapid insertion of new materials, development of new configurations, hardware, and manufacturing methods. Certification time reduction requires better exploitation of modeling and simulation, and better integration of experiment and simulation.

3.5 Summary

Space systems are a very new frontier for flight structures. Of course flight structures has a very different meaning than it does for aircraft, put the challenges for space system structures are in many ways more complex and more rewarding that aircraft structures. The fact that these systems must be packaged, transported and deployed with no deviations from plan makes the space systems business very challenging. The variety of loads and the requirements for thermal energy management is another feature of these systems that poses a challenge.

Military space systems are to a large degree usually “black.” On the other hand, Dr. Lisa Hill of Northrop-Grumman has provided an excellent, unclassified, overview of Space System materials and structures technology needs and directions for military systems. Her PowerPoint presentation is included in the Appendix to this report.

We predict that the mission of Space systems will change during the next 50 years, moving from communications and surveillance to active defensive as well as space combat systems. This movement will trigger migration of National space assets to higher orbits, requiring new thinking about structural configurations such as antennas. The tremendous expense of such systems will lead to reconfiguration and reconstitutable systems that can be upgraded without throwing the entire system away. New materials, new mechanisms and new power sources will be required to enable new configurations.

Space system research should include Grand Challenges of deploying reconstitutable and redeployable systems and include the flight structures sub-challenges that enable such systems. This section has outlined six research problems and payoffs involved for this research. This includes not only energy management through multi-functional structures but also metrology, system health monitoring (we call it structural state awareness) and reducing time to market. In the next section we will consider aircraft future developments and identify two areas in need of research. These areas are but two of many areas, but they are also areas in which exploratory research is already underway and areas in which the PI has in-depth familiarity.

4.0 Future Air systems – Broadband capabilities with emphasis on adaptability and system cost

Section 1.1 has presented a summary of general topics that the PI believes to be fruitful efforts for the future. Most of these efforts are a compilation of topics suggested by workshop participants. However, after a full century of powered, heavier than air flight structural design and design research has reached a plateau. The tremendous variety of materials, processes and experience resulting from past research and available for today’s aircraft makes this distinguished record of achievement a hard act to follow. As a result, it is difficult to identify “pressing needs” for current systems. We will however identify several such areas related to emerging systems.

Figure 4-1 shows the wide variety of aircraft structural requirements that exist today. In nearly every area, disciplines such as structural mechanics have made contributions. This is particularly true in such as computational aeroelasticity and fatigue prediction. On the

other hand, air vehicle systems are on the verge of a revolution in both doctrine and technology. Two threats face the U.S. during the next half-century: 1) challenges from low intensity adversaries that we now face in Iraq and Afghanistan; and, 2) challenges from peer or "near-peer" competitors such as Iran and China. Because of the challenges from low intensity groups, one major feature of technology development during the next half-century will be the change in the acquisition paradigm. This change is illustrated in Figure 4-2.

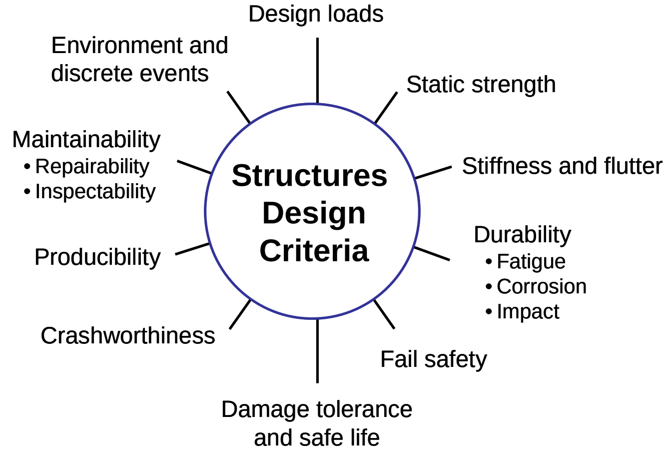

Figure 4-1 – Structural design requirements (Charles Saff-Boeing)

Figure 4-2 illustrates that, unlike the aircraft development and acquisition of the 20th Century, the 21st century has already brought two significant changes to our acquisition and development system. The first change is the end of large numbers of combat aircraft "buys" other than those already underway. The F-35 is the last manned fighter aircraft to be developed for the next few decades. New manned aircraft acquisition most likely will be confined to the tanker fleet, although a Long Range Strike Bomber is a possibility.

A second major change is the changing role of the Air Force as the United States shifts to a war on terrorist groups who are widely dispersed in remote locations throughout the world. While these groups are not peer groups in a military sense, they defy action in a systematic military battle sense. As a result, the surveillance and reconnaissance function of the Air Force and other military services has become much more important. In fact, we might add the adjective "armed" to these two functions.

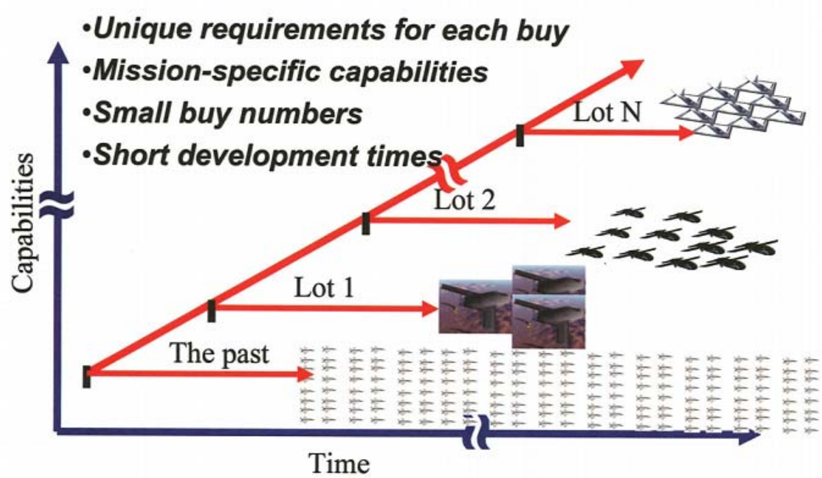

Figure 4-2 –A new military aircraft acquisition paradigm for the 21st Century (Dr. Ravi Chona, AFRL/VA)

Because of this latter activity and combined “hunter/killer” system function, airplanes are likely to come in all sizes, forms, speed ranges and price ranges. Future aircraft are likely to be acquired in small numbers, for special missions, with a premium on responsiveness to threats. We will expect airplanes to be conceived, designed, built, tested and manufactured in 18 months or less. However, the cost must be reduced and large OEM’s (Original Equipment Manufacturers) are not likely to find the development financially lucrative.

A second area identified by interviewees, workshop participants and other is the subject of high speed, hypersonic flight. In addition to the obvious interest in new engines, the continuing interest in high temperature structures was at the top of many people’s lists. “Energy management” is a popular term for the challenges facing high temperature structures designers. Dr, Ravi Chona has addresses this topic in presentations, both at the workshop and at the SDM Panel presentations. His PowerPoint presentation is attached in the Appendix to this report.

For flight structure experts, research progress will require changes in the way we conduct design and development efforts. The challenges of rapid, innovative development and fielding of new weapons will involve every facet of flight structures involving new materials, new manufacturing processes, new analytical approaches, rapid certification and integrated design processes.

4.1 A systems level approach to anticipate change

Several systems level challenges must be addressed by future air vehicle development. At the systems level, the military needs two capabilities: 1) the ability to generate information that identifies an adversary’s intentions and capabilities to act on those intentions; 2) the ability to apply lethal force in a timely, measured manner. This “measured” capability means that we can apply force at several levels beginning with an individual or very small target and on up to very large targets such as facilities or even large cities. “Timely” means that we can quickly apply the force before the targets move or before defenses have time to develop.

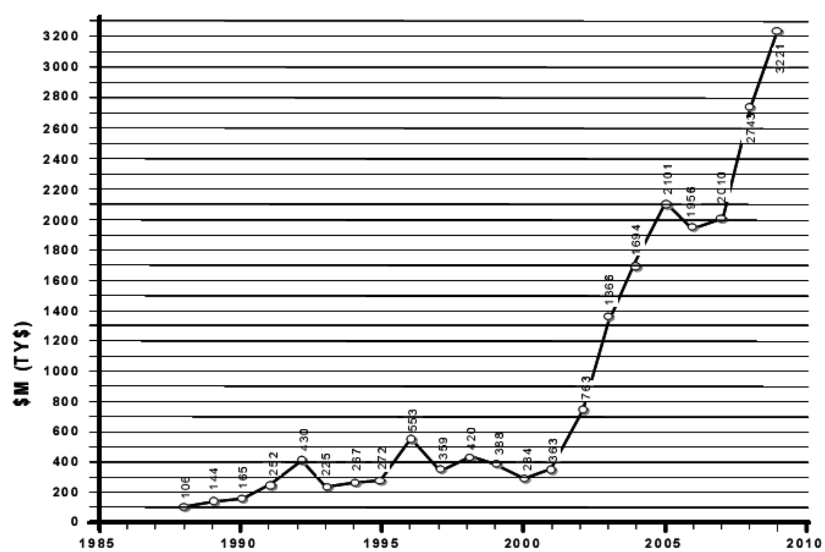

Figure 4-3 – Acquisition expenditures for new unmanned aircraft (See Reference 14, page 8)

We have already discussed the subject of surveillance as it relates to Space activities. In principle, the goal of airborne activities is no different. However, while Space systems operate from the safety of space, airborne systems operate much closer to threats. Airborne systems are subject to loss if they are detected by a hostile, capable adversary. In addition, the operation of airborne systems is very sensitive to logistics, particularly when the systems operate far from a home base. While we might provide 24 hour coverage of an area the cost of doing so enters as a prime factor if the activity takes the efforts of dozens of airplanes, including refueling resources.

To respond to the needs of the military for time-responsive surveillance and lethality at multiple levels, the use of Unmanned Air Vehicles (UAVs) has been a very active area for the past decade. However, as indicated in Figure 4-2, military funding for UAV's is accelerating. This area is probably the most fertile ground for new research into flight vehicle structures.

Despite early successes with Predator and Global Hawk, the senior leadership of the military services has not fully embraced the integration of UAV's into their force structure. In fact, as recently as 2004 the Navy had no UAV's in its operational forces although they have committed to purchasing two Global Hawk aircraft for experimentation.[14]

4.2 New research directions –bio-inspired flight structures and material systems

As mentioned before, we have reached a level of maturity in aircraft design that no one could have imagined fifty years ago. Analytical methods have improved and materials are well characterized. We still have a long way to go to satisfy developers and manufacturing and operations, but a great deal of the work currently being done represents an "epsilon" not a "delta" in achievement. There are notable exceptions.

Many in industry and academia have noted that we have many computer codes but that these codes cannot be put to use easily to stimulate innovation. As mentioned in Section 1.1, several workshop participants called for a broadly based effort to include development of analytical methods that enable rapid insertion of new technology into new systems. New analytical methods are needed to create highly-efficient physics-based methods for use at different levels of a multi-disciplinary simulation environment to foster the ability for virtual design, development, testing and deployment. The workshop participants called this goal "atoms to operation."

There was also a great deal of interest in promoting innovation by means other than running computer codes. The fundamental question is "How do we encourage innovation?" One answer was to facilitate social and organizational changes that lead to "multi-cultural" efforts. In this context, "multi-cultural" means not only combining

[14] **Defense Science Board Study on Unmanned Aerial Vehicles and Uninhabited Combat Aerial Vehicles**, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., February 2004.

different technical disciplines, but combining different roles, such as analyst, designer, test personnel and management (including contracting personnel) to promote cross-disciplinary thinking and "opportunity awareness." The end result is a team effort that might lead to new solutions similar to those required for Grand Challenges.

This project represents a broad survey effort so we cannot go into great depth in any one area. However, since one of the other major recommendations of the workshop participants on air vehicle side included bio-inspired vehicles (the Air Force Research Laboratories is currently interested in flapping flight vehicles for urban surveillance), the PI decided to explore this area further, particularly because this is an area of his own expertise. The focus on small air platforms with different size scales will certainly trigger new developments in materials science and design integration. As a result, the next sections are somewhat biased, but represent the types of efforts at new thinking that we must challenge researchers to do in the future..

Fundamental to the suggestions for future Flight Vehicles research was the recognition of the importance played by new materials in revolutionary design. The workshop participants urged the Air Force to examine novel structural concepts that could be military game changers in terms of their impact on performance, weight or life-cycle cost. These concepts, as suggested by the participants were as follows:

- Adaptive structures such as active wings for load alleviation and mission dependent drag reduction and inlets for efficient propulsion systems
- High strength and stiffness, flexible structures
- Metamorphic structures such as butterfly/cocoon concepts
- Extremely light-weight wings made possible by new materials and materials combinations with the ability to adapt
- Micro-air vehicle structures with efficiencies and performance beyond natural structures and vehicles
- Survivable structures with the ability to change state and repair damage
- Light weight structural systems with heat rejection and control for energetic, high speed flight
- Tailorable 3D composites
- Self-evolving designer structures under the autonomous control of the structure itself-the "learning structure." Materials with the ability to "think," store information, energize and act upon information and unpredictable threats like a living system – a true bio-inspiration.

While mimicking biology is not an end in itself, we can find design inspiration in bio-designs. Wainwright[15] observes. "*So impressive is our ignorance of the sensitivity and response of plants and animals to mechanical information that it is easy to predict a decade of exploration in this field… We will find the time-dependent mechanical properties of structural bio-materials to be the most challenging phenomena to explain. These explanations will surely lead us to new concepts of macro-molecular structure…*"

[15] S. A. Wainwright, W.D. Biggs, J.D. Currey, J.M. Gosline, ***Mechanical Design of Organisms***, Princeton University Press, Princeton, N.J., 1982.

This interest in bio-inspired materials carries over to the systems level. Flexible adaptive air vehicle systems such as morphing aircraft have been proposed and in some cases developed. The term "flexibility" is not used in the structural deformation sense, rather "flexible" systems are defined as "*systems designed to maintain a high level of performance through real time adaptations in their configuration and/or through robust parameter settings when operating conditions or requirements change in a predictable or unpredictable way.*" [16]

Adaptability is defined in Reference 16 as *"a mode of achieving flexible systems where system parameters (design variables) that can be changed and their range of change are identified to enhance performance of the system (for) predictable changes in the operating environment; they can be changed when the system is not in use (passive) or in real time (active)."*

Adaptability requires: 1) innovative design of flight structures to resist loads in diverse flight regimes and mission segments while at the same time changing external geometry and internal properties; 2) integration of power systems and actuators to move material externally and internally to effect the system "state change;" 3) materials and sensors that collect and relay data to places in the vehicle where it is acted upon; and, 4) computers and micro-processors that convert data into information.

Today, many of these functions are done by discrete system components whose inter-relationships are defined by connections that include hydraulics and wiring harnesses. In addition, part of the structural loads is generated by the requirements to support connectors or large power and actuation units.

We must think differently about new systems that do not resemble current systems, either in their function or operation. Morphing vehicles, like reconstitutable space systems can be game changers, but much of the technology required to make the systems realizable does not exist today. This includes materials and design processes. Section 4.3 will examine morphing vehicles, not to recommend the vehicles themselves, but to show how changes in the system create Grand Challenges for the science and technology, including analytical methods.

4.3 Adaptive morphing vehicles - novel structural concepts and configurations

As an example of a significant future trend for flight structures, encompassing demands for integration of materials, power systems and new demands for advanced multi-disciplinary analysis, we will consider morphing aircraft technologies. This area is chosen as a focus because of the PI's familiarity with this area and because it fits the definition of the systems we are trying to promote. U.S. Department of Defense DTO

[16] S.M. Ferguson and K. Lewis, "Effective Development of Flexible Systems in Multidisciplinary Optimization," AIAA 2004-4309, 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Albany, NY, August 2004.

71,[17] defines *morphing* is “a capability to provide superior and/or new vehicle system performance (e.g., agility/maneuverability, range, speed, acceleration, radar cross-section, payload/weapons and sensors, survivability) while in flight by tailoring the vehicle’s state (e.g., physical geometry/configuration, mechanical properties, electromagnetic properties) to adapt to the external operational environment (e.g., atmospheric, electromagnetic) and multi-variable mission roles.”

Unlike military aircraft today, future multi-role morphing aircraft will change their external shape features *substantially* to allow systems to adapt to changing mission environments, including unanticipated threats or challenges. These physical features include re-shaping inlets, re-sizing wings and tail surfaces and re-shaping fuselage dimensions.

Morphing military systems provide agility (the ability to take on new roles), robustness and time responsive action. Shape morphing components such as wings, fuselages and engine inlets, allow aircraft to maintain near optimal operational features and a high level of performance while undergoing predictable or unpredictable, real-time changes in operating conditions.

Despite the remarkable development of new materials, sensors and actuators, it is unusual that we have not seen more “morphing aircraft” develop. Figure 4-4 depicts the large number of variable sweep wings that entered the world’s military aircraft inventory over a period of 30 years. This figure also shows that this number declined rapidly after increasing rapidly. With the exception of the DARPA morphing wing project, no new variable geometry aircraft have been proposed.

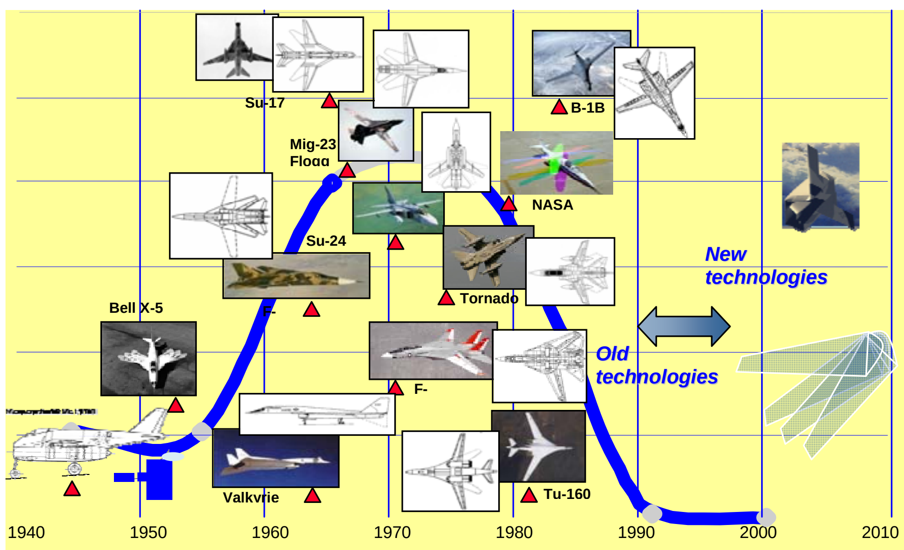

Figure 4-4– Variable sweep morphing wings

Morphing aircraft are distinguished by their ability to change aerodynamic and geometrical features to respond to different or uncertain mission environments. Morphing efforts have been confined primarily to wing design, but is fair to ask “in the

[17] Defense Technology Objectives, DTO 71, DDR&E, U.S. Department of Defense, 2006.

future, how will the general morphing aircraft concept increase military capabilities – and – what morphing features should I develop?”

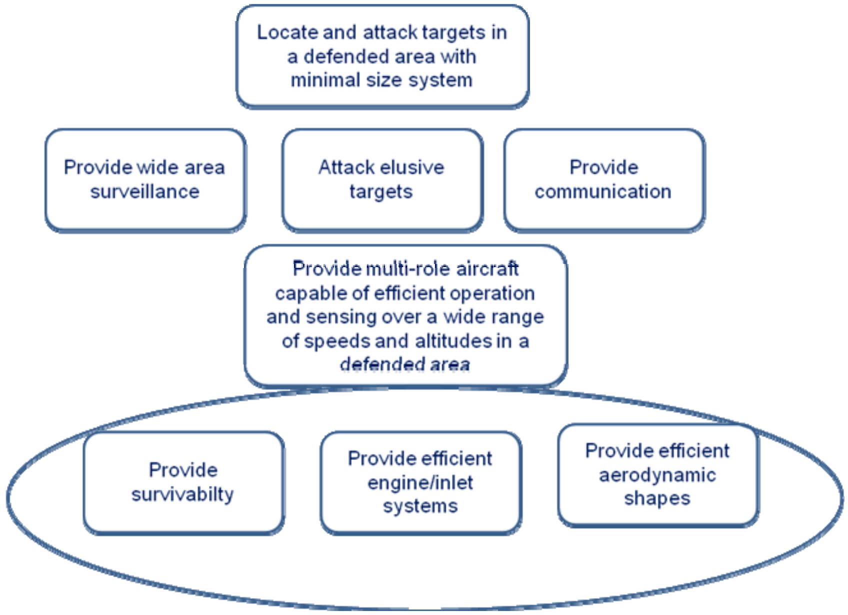

Figure 4-5 – A Grand Challenge with significant Flight Structures contribution

The answer can be found if we consider a Grand Challenge such as that indicated in Figure 4-5. Requirements for speed variations, operational efficiency and minimal size all require compromises for an airplane that may prevent any single design from satisfying one or more requirements. However, the addition of variable geometry as a design feature permits the airplane to assume multiple shapes, each of which are efficient for their mission role. For instance, in the area of survivability, Figure 4-6 indicates that two different shapes might be required to operate in a defended area.

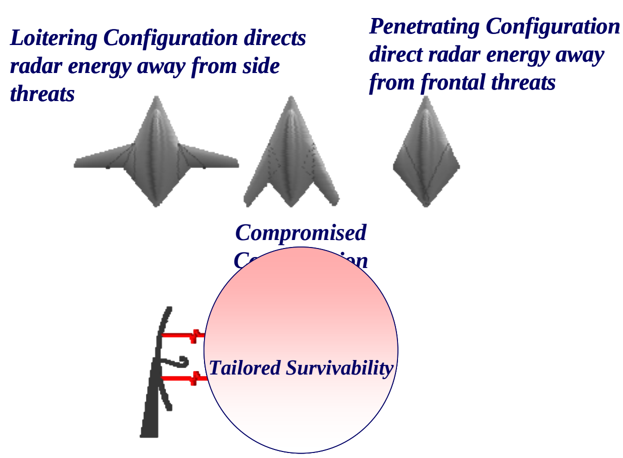

Figure 4-6– Morphing for survivability

The central morphing wing challenge is to create design, fabricate and operate effective integrated combinations of deformable wing skins, actuators and mechanisms, structures, and flight controls to provide an aircraft system designer the freedom to deal with future diverse, conflicting vehicle mission capabilities. Wing cover skins must be highly deformable, but still maintain their shape and structural integrity under compression, tension, shear and bending characteristic of aerodynamic and flight loads. New materials being investigated to meet those requirements include shape memory polymers and elastomers, as well as hybrid composites.

Actuators must meet size/weight/volume, power, force, displacement, and bandwidth requirements. Mechanisms must provide a controlled range of motion with limited

binding/friction. Innovative devices such as thermal active polymers and advanced piezoelectric actuators are being developed to meet these needs. The flight control system and software must be able to adapt to radical shape changes as well as to reconfigure control effectors appropriately for the configuration. New flight control approaches are under development to achieve these requirements.

In addition, the rapid changing of wing surface area and shape creates aeroelastic analysis and design problems that are unprecedented. The prediction of unsteady airloads for such variable geometry surfaces is not within the state of the art today. This means that external loads, structural stability and dynamic response or not available to the designer before testing.

Materials are also a problem, as indicated previously. The materials required for morphing requirements must be multi-functional in ways not anticipated by other programs. To date multi-functional has meant that materials might carry loads while serving another purpose. That requirement, while useful, it far too conservative. Let’s consider truly multi-functional materials and their impact on Flight Structures.

4.4 Multi-functional materials

Materials are at the heart of flight structures development. Because an aircraft must operate at numerous different design points, compromises are required. These compromise also compromise aircraft performance at “off-design” conditions. Multi-functional materials and mechanisms open the door to improved performance at all design points by adapting the materials system and the flight structure to conflicting design points – the challenge of efficient operation at both high speed and low speed is an example.

A vision for multi-functional materials is provided by a DARPA BAA.[18] For this BAA Zakin and Christodoulou have proposed the development of a new class of synthetic, evolvable materials that will enable new capabilities in the functionality, survivability, lethality, and manufacturability of materials for military systems. They define synthetic evolvable materials as non-biological materials that use environmental cues to autonomously self-organize, self-propagate, and self-select specific internal configurations to optimize or maintain system functionality under dynamically changing conditions.

Synthetic evolvable materials require minimal energy input to function, e.g., exhibit auto-amplification, and have an intrinsic "memory" or an embedded instruction set that encodes the present state of the material. Synthetic evolvable materials autonomously adapt their structure/properties to changing external conditions over a broad range of length scales and timescales as required.

Proposed uses of these materials include: engine nacelles with inlet areas that adapt to increased or decreased speed; self-healing/repairing armor hulls; satellites with active

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[18] Dr. Mitchell R. Zakin and Dr. Leo Christodoulou, Synthetic Evolvable Materials, BAA 07-21 Addendum 4; Defense Advanced Research Projects Agency, February 2007.

reconfigurable pointing, thermal management reconfiguration; inflatable, self-rigidizing structures; space systems with adaptive lenses and mirrors; re-entry vehicles with active shape control; aircraft with low observability on demand at various wavelengths; and, soldiers with adaptive body armor, helmets and boots.

Design adaptability requires a long-term goal to create devices and materials that quickly change functionality on demand, using innovative, internal, micro-switching mechanisms. This includes changing, by several orders of magnitude, properties such as mechanical stiffness/modulus, electrical conductivity or thermal conductivity and it also includes localizing these effects to create patterns or zones of radically changed properties.

In addition to DARPA funded researchers, other researchers have proposed the development of a similar, but radically new, class of multi-functional materials called "symbiotic" or "situationally functional" materials. The term ***symbiotic*** describes interactions between two dissimilar organisms living together in intimate association. The larger of the two members or components is the ***host*** or macro-material while the smaller micro-member is the ***symbiont***. Interactions between the host and the symbiont create, on demand, changes in properties of the ensemble. These symbiotic biological or material combinations have the ability to change physical features - on demand - in response to external system stimuli.

Symbiotic materials are a sub-set of active, adaptive, multi-functional, "designer" materials that change key physical properties on demand. Symbiotic interaction turn features on and off. External or internal stimuli such as ultra-violet light, thermal energy, magnetic field, chemical reaction or other energetic stimulus provide this on/off switching. These materials have been proposed to be used in situations where there is no existing material and lead to entirely new devices, ranging from morphing aircraft to lighter weight armor.

Symbiotic materials are not the traditional multi-functional materials because they are not necessarily multi-use passive structures or a single property active material. Instead they are multi-use materials with multiple properties that are switchable from one state to another. Symbiotic materials are a different kind of "smart" materials. Symbiotic materials need not be primary load-bearing structures. Symbiotic materials might only have the capability to provide thermal management or electrical reconfigurability.

Thermal conductivity is an example of a material function that would benefit from a change during a mission. As mentioned in Section 3, satellites reject heat during some portions of the mission, but also be insulated to protect the system from heat during other mission segments. Generally this takes two very different types of material or requires mechanical louvers to open and close as the spacecraft passes in and out of the Sun.

Substituting material dominated designs for mechanism dominated designs, mechanisms like louvers, reduces system weight and changes system shapes. Providing variable electrical conductivity can liberate designers so that they can adopt different geometries

without compromising LO survivability. Designer freedom and design efficiency are the payoff for symbiotic materials development. Like their cousins, the multi-functional materials, symbiotic materials are multi-functional. Unlike multi-functional materials, symbiotic materials are situationally functional since they can be turned on or off.

How do we develop symbiotic materials? The only thing that is clear at this early stage is that a combination of physics, including chemistry, and mechanics, micro-mechanics or macro-mechanics, holds the key to symbiotic materials development. A related question is *"how do we model these materials?"*

Key research questions include:

1) How can the materials be stimulated, controlled and localized? What are the alternatives to heat or ion transport? How effective is using an electric field or light?
2) What base/host materials could be used?
3) What are the limits to different stimulation methods (e.g. light, electric field, thermal …) and materials (polymers, inorganic materials …)?
4) How can we make the transition occur rapidly?
5) What basic structural models can be used to help explain the concepts and to explore the useful limits?

4.5 Aircraft Summary

There are a myriad of challenging research problems being addressed today and even more that could be addressed in the future. These future areas include: hypersonic flight; reducing JP-8 energy use; developing efficient power sources; developing low drag, light-weight lifting surfaces; developing modular structures; and, improving testing or reducing time to market at the developmental level. All of these areas were serious topics raised by workshop participants.

On the other hand, Section 4 has ignored serious issues such as research related to sustainment. These issues primarily relate to research related to the topics shown in Figure 4-1. Instead we have focused attention on bio-inspired vehicles; we did this for several reasons. First of all, it is an area that the PI has had a long association an extensive knowledge. However, in my own defense, it is not the building of such vehicles that is advocated. Instead, it is the use of these vehicles as Grand Challenges that will ultimately produce new materials, new integration challenges, new analytical techniques and new thinking that will permeate the traditional fields of aircraft engineering.

In Figure 4-2 Dr. Ravi Chona presents a vision of the future with small numbers of small aircraft that require changes in testing and development, not to mention reduced cost and time to market. These are issues that, if resolved, will spill over to the traditional aircraft development.

Bio-inspired vehicles pose challenges to the research community, not because we seek to emulate Nature's designs – our materials are better and our aircraft operate in a much

higher speed range - but because we seek to emulate Nature's design approach. This includes exquisite design integration and highly efficient operational efficiency. Drilling down to the Grand Challenge of aircraft such as morphing aircraft – one of many examples that we could have chosen – we see that materials are important, but so too are analytical areas such as aeroelasticity. For instance, we simply do not have the aeroelastic tools to simulate advanced morphing wing dynamic response and stability. In addition, no one in the community has stepped up to remedy this deficiency.

We have also identified the need for analytical tools and processes to foster innovation. The meaning of "foster innovation" is very fuzzy, but at the highest level one should ask, "can these tools – in the hands of competent designers - create new revolutionary designs or lead to discovery?" MDO optimization tools are an important part of this effort but regrettably the efforts in this area are geared to "business as usual." Where is the new Lucien Schmit to inspire this community?

Multi-functional material development is similarly stuck in the 1990's. The DARPA BAA, now in its Phase 1 development is a good start but cannot be relied upon to provide the needs of the aircraft community. We are still comfortably wrapped in limited goals for these materials and very little really fundamental research to answer questions such as those posed at the end of Section 4.4. Solving problems in this area and the spin-offs from these solutions are essential to future flight structures progress.

5.0 Lessons learned and suggestions for the future

This research effort began as a very noble cause, the identification and cataloging of first-class, revolutionary, cutting edge research projects. This was not the first time I had been involved in such efforts and the intent was to "do it right this time." One hopeful sign was the close connections with leading researchers that had been created by my four year service at DARPA. In fact, those associations produced the most fruitful information and advice. However, it soon became obvious that a major difficulty lay in wait for the unsuspecting searcher. That difficulty is the inertia of the research community and some frustration by the funding community that there is not more freedom of action.

Let me explain the research community inertia. Government laboratory research is closely tied to area plans that have exquisite detail and are in well-developed. However well intentioned, there are two major problems with these "road maps." The first is that the road maps change with leadership and leadership changes all too often. The second problem is that there usually is not enough flexibility to investigate "wacky" concepts. There is never enough money to fund all interesting ideas and the approval process is far too long. The only solution to this is persistence.

Another problem with identifying and launching new efforts is the inertia of the research community. The academic community enjoys picking the daisies in the field near them. They persist in doing what is comfortable. Some researchers have made a life's work at studying the same problem or some variation of it for their entire career. Others have strong track records of branching out and expanding. There are too many of the former

and too few of the latter. Given the strong pressures to publish and secure funding or perish, this is not likely to change.

This effort produced fewer results than I had hoped. However, there are three major results that I believe are useful. The first was bringing together expert researchers to consider three questions "where are we going," "where should we go?" and "how do we get there?" The discussions that these questions produced were valuable for all involved. A second result is a list of suggested topics. In Sections 3 and 4 I have chronicled the answers to these questions as I have interpreted the answers given to me. A third result is a process of defining Grand Challenges and working the definition of these challenges down to lower levels to define disciplinary research areas.

As mentioned before, the answers to these questions are filtered through the listener's experience. That experience in my case is heavily weighted towards a recent DARPA experience. Like all government agency program managers, DARPA Program Managers listen and then assemble the results into programs. On the other hand, because they deal with an ensemble of industry, government and academic proposers, the DARPA answers sometimes are different than those others might get. DARPA managers usually think about devices rather than technologies and note, after the fact, the absence of adequate analytical efforts. As a result, my presentation is biased.

5.1 Developmental workshops

To tap into the reservoir of expert knowledge in the U.S. technical community and encourage free-wheeling thinking there should be at least two developmental workshops each year. One workshop should occur at the systems/capability level and produce Grand Challenges. At this level, system operators and developers should be consulted and challenged to provide their dream lists of new capabilities. Then, an "objectives tree" like those shown in Figures 1-4 and 1-5 should be developed. Academics should also be included in this effort even though they may function largely as observers. Participants for this effort should not be limited to only one discipline.

For the second workshop, a grass-roots, bottom up effort should be conducted. This effort should use the results of the first workshop to address scientific, analytical and testing efforts that support the Grand Challenges. Academic researchers are usually valuable for this effort, but industry and government personnel are also required. For this effort a variety of researchers should be enlisted. If there is a way to tap into the large number of experts at National meetings then this would be useful. The problem with National meetings is the absence of large numbers of industrial participants.

5.2 Strengthening government laboratory collaborations with industry and academia

As the result of this effort and previous experience at DARPA, I noticed that the people who were collaborating with government laboratories such as AFRL are different than those being funded by DARPA. One reason is that the projects in the laboratories seem to be more focused on sustainment. For industry-academic collaboration, the MURI

model is a great success, but MURIs are few and far between and ultimately become concentrated in one or two institutions. AFOSR supplies substantial funding to first-class AFRL researchers. Investigating high risk research topics (quick in and quick out) with collaborative teams of academic and industrial participants in areas identified by Grand Challenges has merit, but the format and organization has to be carefully planned. The bottom line is that idea generation and preliminary investigation has to be encouraged in a team environment and ideas and concepts need to be validated or discarded.

5.3 Conclusion

As the result of this investigation, several promising areas of research related to integrated flight structures science, technology and computational methodology have been identified. Many of these areas reflect the background of the investigator and the experts who participated in the process. A common theme running through the suggested research is the interdisciplinary nature of flight structures and the need to combine diverse technologies into innovative systems. This goal has been referred to as "atoms to aircraft" and is an ongoing quest. The need to develop software is obvious and always with us, but also in question is whether or not the mathematics we currently use to describe interactions cannot be improved or changed, not just applied to faster computers.

New configurations such as small flapping vehicles and bio-inspired vehicles pose new challenges for power systems and structures. Once again, integration is a large problem. In the Space Systems area, the tendency to move assets to higher orbits demands greater attention be paid to large deployable antennas. The need for multi-functional structures and energy management within the structure is not only a problem with Space Systems, but it is a problem with high speed vehicles (for which there are no bio-inspired counterparts).

Finally, it is the constant struggle between the research establishment and the newcomers that produces the biggest surprises. Leaving the door open to funding of high risk research, at least at the exploratory level, produces "I told you so" failures but also astounding results.

6.0 Appendices – List of participants at October 2007 Workshop[19] *and PowerPoint presentations*

Banks, David	Boeing Seattle	david.l.banks@boeing.com
Cesnik, Carlos	Michigan	cesnik@umich.edu
Chase, Charles	Lockheed-Martin-Palmdale	charles.chase@lmco.com
Chen, Dan	Boeing/Huntington Beach	daniel.chen2@boeing.com
Chona, Ravi	AFRL/VA	ravi.chona@wpafb.af.mil
Christodoulou, Leo	DARPA	Leo.Christodoulou@darpa.mil
Dean, Peter	Lockheed-Martin	peter.dean@lmco.com
Dowell, Earl	Duke University	dowell@ee.duke.edu
Engelstad, Stephen	Lockheed-Martin Marietta	steve.engelstad@lmco.com
Fillerup, James	AFOSR/SOARD	James.Fillerup@AFOSR.AF.MIL
Fuller, Joan	AFOSR	joan.fuller@afosr.af.mil
Giurgiutiu, Victor	AFOSR	victor.giurgiutiu@afosr.af.mil
Haugse, Eric	Boeing/Huntington Beach	eric.d.haugse@boeing.com
Heinimann, Markus	Alcoa	markus.heinimann@alcoa.com
Hill, Lisa	Northrop-Grumman Space	lisa.hill@ngc.com
Lee, B. L. (Les)	AFOSR	ByungLip.Lee@afosr.af.mil
Lesieutre, George	Penn State	g-lesieutre@psu.edu
Lewis, Mark	USAF	Mark.Lewis@pentagon.af.mil
Mann, Ben	DARPA	bmann@darpa.mil
McGowan, Anna	NASA	a.r.mcgowan@larc.nasa.gov
Morton, Scott	AFRL/MN	scott.morton@eglin.af.mil
Ng, Kam	ONR	ngkw@onr.navy.com
Reifsnider, Kenneth	University of South Carolina	reifsnid@engr.sc.edu
Russell, Thomas	AFOSR	donna.turner@afosr.af.mil
Scarcello, John	Lockheed-Martin	john.scarcello@lmco.com
Weisshaar, Terry	Purdue University	weisshaar@purdue.edu
White, Edward	Boeing St. Louis	edward.v.white@boeing.com
Wilson, Peter	Sandia	pjwilso@sandia.gov

The following PowerPoint presentations were presented during the course of this research and are submitted for consideration.

[19] This is a list of attendees, but not all participated in the full two day workshop. For instance, Dr. Mark Lewis attended only the morning session of the first day.